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Nuclear Engineering and Design 237 (2007) 2265–2274
Nuclear Engineering and Design
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Economic potential of modular reactor nuclear power plants based on the Chinese HTR-PM project

Zuoyi Zhang*, Yuliang Sun

Institute of Nuclear and New Energy Technology (INET), Tsinghua University, Beijing 100084, China

Received 5 March 2007; received in revised form 11 April 2007; accepted 11 April 2007

Abstract

Modular reactors with improved safety features have been developed after the Three-Mile Island accident. Economics of small modular reactors compared to large light water reactors whose power output is 10 times higher is the major issue for these kind of reactors to be introduced into the market. Based on the Chinese high temperature gas-cooled reactor pebble-bed module (HTR-PM) project, this paper analyzes economical potentials of modular reactor nuclear power plants. The reactor plant equipments are divided into 6 categories such as RPV and reactor internals, other NSSS components and so on. The economic impact of these equipments is analyzed. It is found that the major difference between an HTR-PM plant and a PWR is the capital costs of the RPV and the reactor internals. The fact, however, that RPV and reactor internals costs account for only 2% of the total plant costs in PWR plants demonstrates the limited influence of this difference. On the premise of multiple NSSS modules forming a nuclear power plant with a plant capacity equivalent to a typical PWR plant, an upper value and a target value of the total plant capital costs are estimated. A comparison is made for two design proposals of the Chinese HTR-PM project. It is estimated that the specific costs of a ready-to-build $2 \times 250\,MW_{th}$ modular plant will be only 5% higher than the specific costs of one $458\,MW_{th}$ plant. When considering the technical uncertainties of the latter, a $2 \times 250\,MW_{th}$ modular plant seems to be more attractive. Finally, four main points are listed for MHTGRs to achieve economic viability.

1. Introduction

Since the modular high temperature gas-cooled reactor (MHTGR) concept was proposed by Reutler and Lohnert of SIEMENS/Interatom at the end of the 1970s, its inherent safety and the concept of modularization have been widely adopted within the nuclear community. Nevertheless, can nuclear reactors of about $200\,MW_{th}$ compete with large-scale light water reactors whose power output is more than ten times as large? This question has been constantly under discussion and has become the major issue for an MHTGR to be introduced into the market. However, this is not only a question for the MHTGR; after the Three-Mile Island and Chernobyl nuclear accidents, a series of advanced reactor concepts with inherent or passive safety features were proposed in order to improve nuclear safety. One common feature of all these reactor designs is the down-scaling of the reactor power to several hundred Megawatts in order to solve the problem of passive decay heat removal and to make sure that the reactors will not melt. How these low power nuclear reactors can compete with modern large-scale nuclear power units whose thermal power is several thousand Megawatts has become the main challenge for this type of reactors with inherent safety properties.

After having proposed the modular reactor concept, Reutler and Lohnert published several papers, intending to show that pebble-bed MHTGRs also possess economic competitiveness besides their inherent safety features. In reference Reutler and Lohnert (1984), the authors show that a nuclear power plant composed of multiple reactor modules should be competitive to coal-fired plants. As the costs which depend on the reactor core design accounts only for about 20% of the total construction costs of a nuclear power plant, the increase or reduction of power output per module in a multi-module power plant would not have significant impact on the plant capital costs. In reference Kugeler and Froehling (1993), the specific capital costs of a power plant with 2-modules, 4-modules and 6-modules are, respectively, analyzed. It is shown that the plant specific capital costs will decreases for batch construction so

* Corresponding author.
E-mail address: zyzhang@tsinghua.edu.cn (Z. Zhang).

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doi:10.1016/j.nucengdes.2007.04.001

that a 6-module plant of batch construction could possibly compete with a 1200 MW_e PWR plant. In 1993, the reports published by the American GCRA (1993) made analyses on the plant capital costs of the lead module, a 4-module prototype plant, the replica plant and the target plant of the MHTGR (450 MW_{th}) design. Recently, the paper published by Wallace et al. (2006) analyzed and compared the number of systems of the South African PBMR and pressurized water reactors, and showed the cost impact of the systematic simplification of the PBMR. A significant cost reduction of modularization was shown.

In the 1980s, SIEMENS/Interatom Company in Germany committed itself to constructing a 2-modular HTGR demonstration plant. It accomplished much research and development. The safety analysis report was reviewed by relevant German licensing bodies. The American General Atomics Company carried out in-depth research and development work for the 350 MW, 450 MW steam cycle MHTGR designs and a 600 MW gas turbine cycle GT-MHR design. South Africa has been developing a pebble-bed modular reactor (PBMR) since the middle of 1990s, from the very beginning adopting the gas turbine cycle. The recent design features a reactor of 400 MW thermal and 165 MW electric power. Japan has built the prismatic high temperature gas cooled test reactor HTTR (30 MW_{th}) in 1997. China began research work on pebble-bed high temperature gas cooled reactors at the end of the 1970s. In 1992 the Chinese government approved to build the pebble-bed test reactor HTR-10 with 10 MW thermal power at the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University, Beijing. Construction of the HTR-10 started in 1995 and the reactor achieved criticality in December 2000. In January 2003, it achieved full power and was connected to the power grid. From January 2003 to April 2006, the reactor was operated for 465 days and a batch of experimental verification work were carried out, including ATWS experiments as well as loss of heat sink, control rod withdrawal, etc.

On the basis of the HTR-10, the high temperature gas-cooled reactor pebble-bed module (HTR-PM) Project is proposed. The major target of the HTR-PM Project is to build one pebble-bed MHTGR demonstration plant of 200 MW_e around 2013. The main technical objectives are:

(1) to demonstrate the claimed inherent safety features of the system,
(2) to help reveal the potential economic competitiveness,
(3) to reduce technical risks, employing the rich experiences made with the HTR-10 and other mature industrial technologies, and
(4) to provide a sound basis for achieving modularized design and construction.

Among the above objectives, the most difficult key-issue of the HTR-PM demonstration plant will be to show that an *N*th-of-its-kind HTR-PM plant will be economically viable.

This paper is going to show the economic potential of an HTR-PM plant. The data given are based on the already acquired experience of the HTR-PM Project gathered by INET since 2001. The article is an attempt to depict a workable technical route for the development of a modular HTGR from the viewpoints of many techno-economical aspects.

2. Studies on important concepts

2.1. Safety aspects of HTR-PM plants

We believe that an HTR-PM plant should have the following safety features:

(1) When the reactors are working at normal operation conditions, the radioactive inventory in the primary helium is very small. Even if this limited amount of radioactivity would be released into the environment following an incident/accident, there is no need to take emergency measures such as sheltering, or evacuation.
(2) For any conceivable conditions of reactivity accidents or for any failure of the residual heat removal system, the rise of the fuel temperatures will not cause a significant additional release of radioactive substances from the fuel elements. This can be controlled by measuring the gaseous radioactivity in the primary system.
(3) The consequences of water or air ingress depend on the quantity of such ingresses. The ingress process is slow, and can be terminated easily within several dozens of hours (or even days) by taking very simple actions. The possibility for the failure of such simple actions can be excluded.

2.2. Definition of modular designs

Module concept I: One large system is divided into several identical subsystems, and these subsystems are called modules. Their characteristics are:

(1) the subsystems are completely identical;
(2) each subsystem is relatively simple;
(3) as far as reactors are concerned, it is best that they have independent safety functions.

Module concept II: One large system is divided into several different subsystems. They have the following characteristics:

(1) each subsystem is relatively small and easy to be assembled in a factory;
(2) each subsystem is different from all others;
(3) in term of reactors, if one module is devoid, the safety function may be incomplete.

The module concept I is different from the second concept. The latter is more a package. This paper discusses only the module concept I because it can take the maximum advantages of the benefits brought by modularization. The benefits mainly include:(1) economics of experience and (2) economics of scale.

Economics of experience refers to the effect suggested by the so-called learning curve.

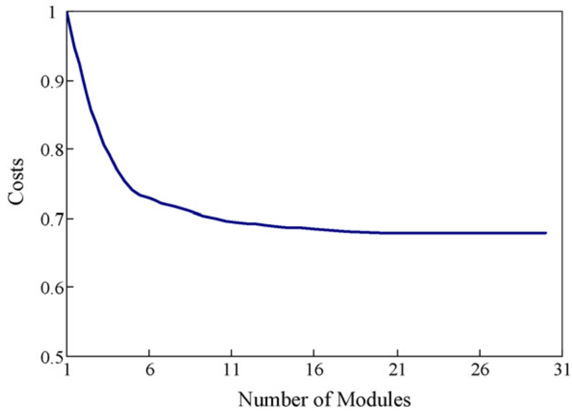

Fig. 1. Learning curve.

Fig. 1 presents a typical learning curve. It indicates that cost is reduced as subsequent modules will gain from the experience made by manufacturing preceding modules. The curve will reach its minimum after about the 10th module. The maximum cost-decrease is around 30%. This curve is also applicable to large-scale pressurized water reactors. However, as the plant capacity of pressurized water reactors is large and number of orders is limited, the effects of learning curve cannot be fully utilized.

Economics of scale refers to the economic benefit due to the increase of production. The cost is divided into fixed cost and variable cost. Variable cost increases with the increase of output, such as raw materials, power and so on; while fixed cost do not increase with the rise of output, such as factory building, equipment, design, marketing, management and so on. When the output increases, the specific variable cost remains unchanged, while the specific fixed cost is in inverse proportion to the output, i.e. it decreases with the rise of output. Suppose, e.g., the pressure vessels are manufactured with 60% variable cost, such as the forgings, plates, welding materials and power, while the remaining 40% is fixed cost. The cost of manufacturing 10 pressure vessels can thus be reduced by 30% compared to manufacturing 2 pressure vessels only.

2.3. Plant and NSSS module

The economics of nuclear power plants depends on the operational cost per kilowatt-hour and the capital cost per installed Kilowatts. The economics of one MHTGR and of one PWR nuclear power plant must be compared on the basis of equal plant capacity. For MHTGR plants it is obvious to adopt multiple NSSS modules for one plant.

In an MHTGR nuclear power plant with multiple NSSS modules there should be only one control room to monitor and control all NSSS modules, the turbine-generator and its auxiliary systems. Most auxiliary systems should be shared among all the modules, with the exception of the reactor protection system and other relevant nuclear safety systems. The calculation of CDF is based on one plant consisting of multiple NSSS modules.

Fig. 2 shows a proposed future HTR-PM plant. In this HTR-PM plant, 6–10 NSSS modules, 100 MW_e each, are adopted and share the electrical and the auxiliary system building. The plant consists of one steam turbine generator and one control room only. The subsequent analyses are carried out for such a multiple NSSS module plant.

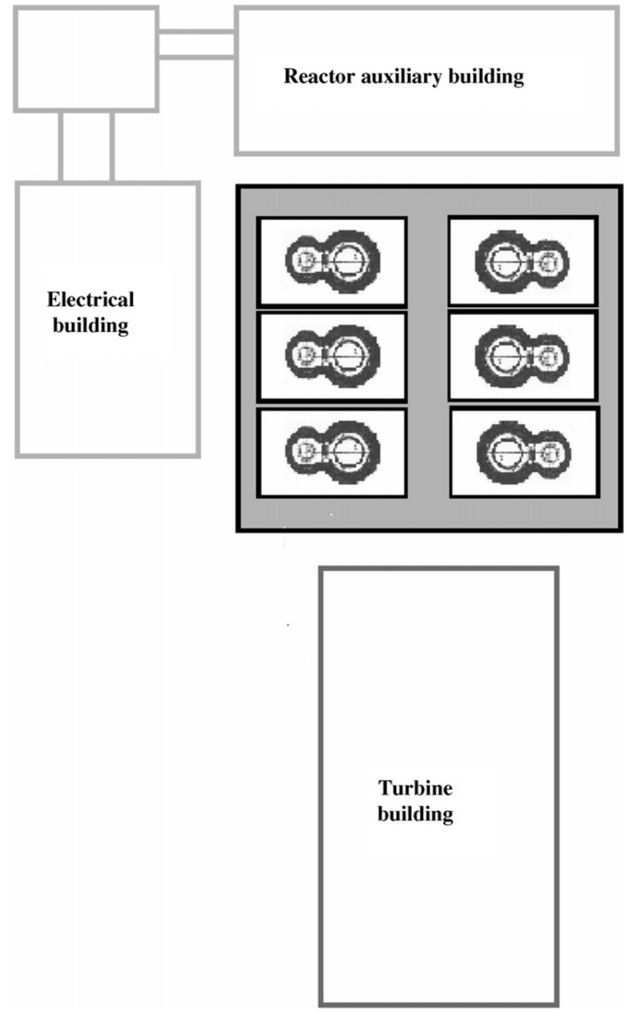

Fig. 2. HTR-PM plant with multiple NSSS modules.

3. Two HTR-PM designs

To find a final standard design of an HTR-PM plant INET has intensively studied two different designs since April 2004.

3.1. 1 × 458 MW_{th} module with a two-zone core

This kind of design adopts a fuel-free graphite zone in the center of the pebble-bed to guarantee that the highest temperature of fuel elements will never exceed fuel temperatures of 1600 °C under any depressurization accident, whereby the power output of a single module had been stretched as much as technically possible. Detailed evaluation was undertaken for a fixed and for a dynamic central column. The advantages and disadvantages of the two alternatives of this type were studied. The overall conclusion was that both solutions are feasible, although both designs of this type have certain technical uncertainties. Considerable verifications are needed to overcome these uncertainties.

Table 1
Key design parameters of HTR-PM

Parameters	458 MW	2 × 250 MW
NSSS modules	1	2
Core thermal power (MW)	458	500
Diameter of core inner reflector (m)	2.2	0
Diameter of core outer reflector (m)	4	3
Core height (m)	11	11
Primary helium pressure (MPa)	9	7
Core outlet temperature (°C)	750	750
Core inlet temperature (°C)	250	250
Fuel enrichment (%)	9.5	8.9

Table 1 presents the general design parameters. Fig. 3 shows the cross-section of the reactor.

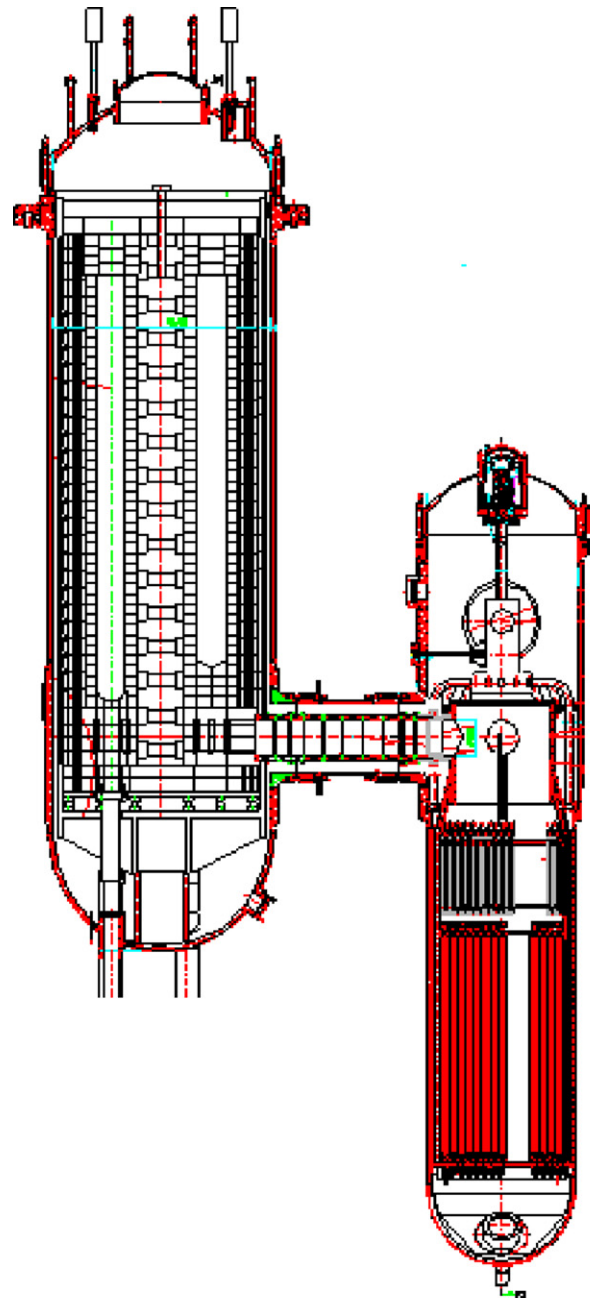

Fig. 3. HTR-PM reactor design of $1 \times 458\,MW_{th}$—two zones core.

3.2. $2 \times 250\,MW_{th}$ modules with one-zone core

This kind of design adopts a one-zone pebble-bed reactor core. According to the research results of the recent 20 years, the power of the modular core is increased from 200 to 250 MW thermal while keeping the same inherent safety features. As China has already built the HTR-10 reactor, adopting the side-by-side arrangement of the reactor and steam generator, and is currently operating it successfully, the $250\,MW_{th}$ one-zone module is an up-scaling of the HTR-10. Hence, in essence, the HTR-10 can be regarded as the prototype of the large modular design of 250 MW thermal power. Obviously, the 250 MW design can benefit from all the lessons learned during design, construction and operation of the HTR-10. This will minimize technical risks. Fig. 4 shows the cross-section of the reactor. Fig. 5 displays the horizontal cross-section of the reactor building in both designs.

4. Economics of an HTR-PM

4.1. Break-down of PWR capital costs

Fig. 6 presents the typical break-down of the capital costs of a $2 \times 1000\,MW_e$ PWR. The total costs of all the PWR plant are normalized to 100. Among them, reactor plant equipments account for about 23–28%, depending on ways of delivery. Turbine plant equipments take up about 12% and BOP is about 3%. These are so called direct costs. Other costs include the costs for design, engineering service, project management and financial costs, etc.

The indirect costs should be estimated according to the actually required workload and materials. These costs may be not in proportional correspondence to the capital costs of equipments. Based on the above explanations on the indirect cost, reactor plant equipments take up about 23–28% of the total plant cost, which shows that the influence of the different reactor plant equipments on the total investment should be reduced, while the effective project management may have great impact. Modularization design is likely to simplify engineering, project management and shorten project schedule.

Fig. 7 shows the capital costs break-down of PWR reactor plant equipments. According to our analyses, reactor plant equipments are divided into 6 categories. The only difference to a traditional classification is that in our case the NSSS equipment is further subdivided into Reactor Pressure Vessel (RPV) and reactor internals, as well as other NSSS components.

- RPV and reactor internals.
- Other NSSS components: steam generators, primary pipelines, pressurizer, control rods, main pump and so on.
- Reactor auxiliary systems: emergency reactor core cooling systems, decay heat removal systems, containment spray system, and chemistry and volume control system, etc.

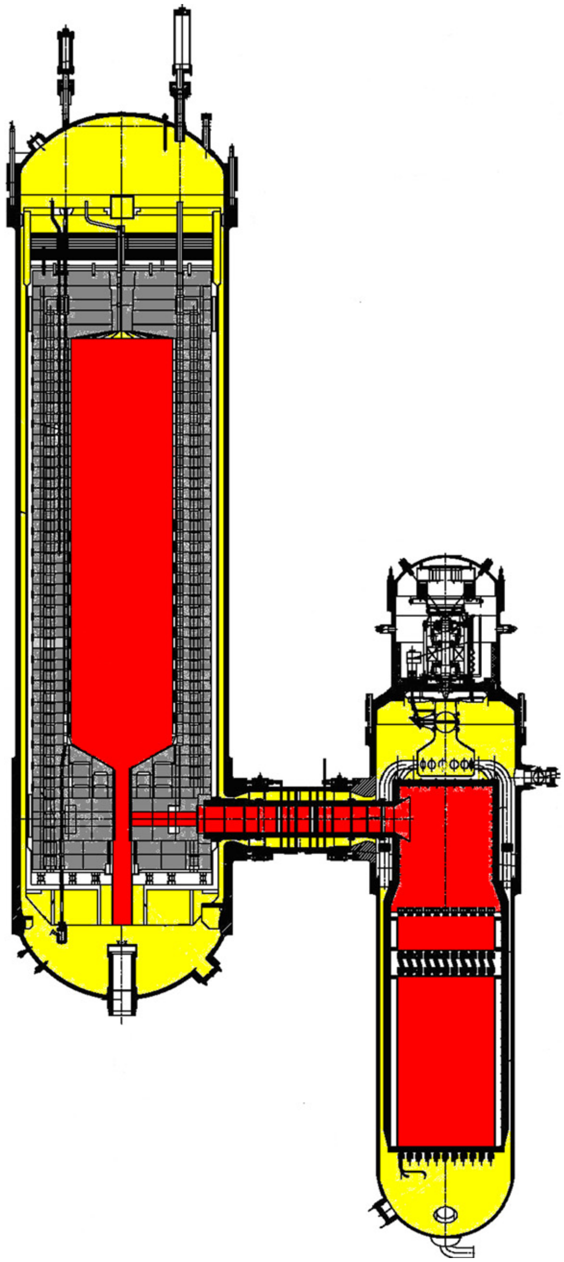

Fig. 4. HTR-PM reactor design of $2 \times 250\,MW_{th}$—one zone core.

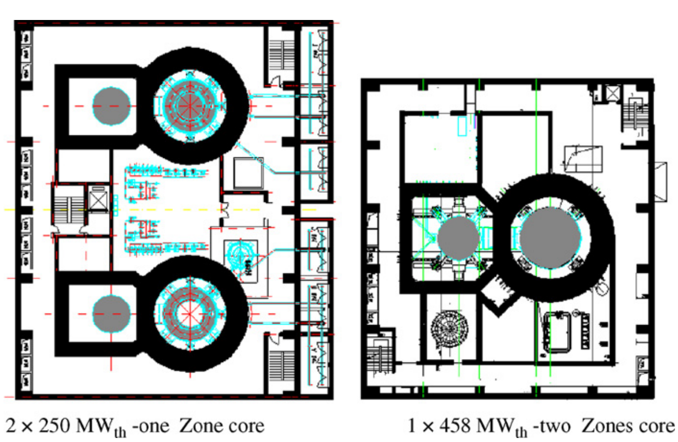

Fig. 5. Cross-section of the two HTR-PM reactor building designs.

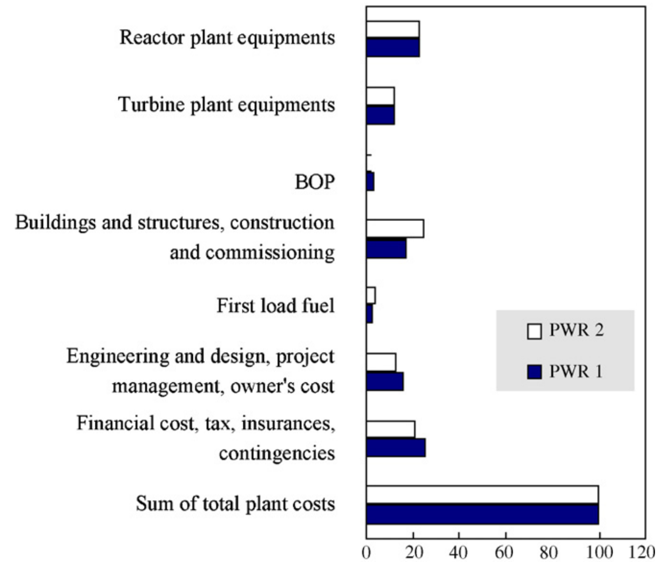

Fig. 6. Capital cost break-down of PWR total plant.

- I&C and electrical systems: reactor protection system, control room, instrumentation, emergency diesels, batteries and so on.
- Fuel handling and storage: the temporary storages of fresh and spent nuclear fuels, fuel handling systems.
- Other components in reactor plant: cranes, communication system and other reactor plant equipment.

Considering the total costs of the above-classified reactor plant equipments, the costs of the RPV and the reactor internals account for about 9%, the reactor auxiliary systems for about 23% and the I&C and electrical systems for about 26%. Thus, the costs of RPV and reactor internals, compared to the total plant cost will be about $9\% \times 23\% = 2\%$. This shows clearly that the RPV and the reactor internals of PWR-plants exhibit only a very limited influence on the total plant cost.

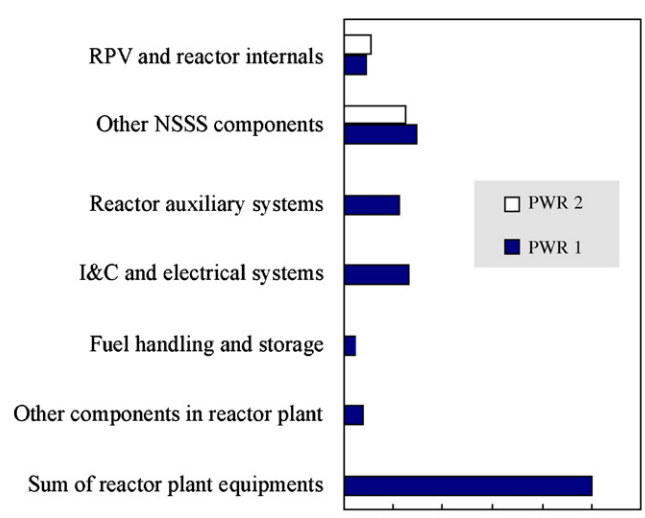

Fig. 7. Capital cost break-down of PWR reactor plant equipments.

Table 2
Comparison of key NSSS equipments

HTR-PM	PWR	Description
RPV, reactor metallic, graphite and carbon reactor internals	RPV, reactor internals	Specific cost of HTR-PM(*USD/kWe*) in the two equipments is about 8 times of those in PWR
Steam generator heat transfer bundle	Steam generator heat transfer bundle	HTR-PM steam generator has lower heat transfer coefficient and higher temperature difference. Specific heat transfer area(M^2(*heat transfer area*)/MW_e): PWR is 20, HTR-PM is 20
Helium blower, non-safety related	Coolant pump, safety related	HTR-PM has lower coolant density and higher temperature increase. Specific Pump/blower power (*kW*(*required to drive the motor*)/MW_e), PWR is18–32, HTR-PM is 30
Control rods and its driving systems, Small sphere absorption systems	Control rods and its driving systems Boron injection and chemical system	Cost of HTR-PM is similar to PWR
Connecting vessel, steam generator vessel	Main coolant pipe, pressurizer, steam generator vessel	PWR is expensive than HTR

4.2. *Technical features of HTR-PM reactor plant equipments*

Table 2 gives the main NSSS equipments of HTR-PM and compares them with the corresponding PWR equipments.

4.2.1. *RPV and reactor internals*

The inherent safety features of MHTGRs are based on the fact that the core power density is chosen such that for any conceivable accidents the fuel elements will not surpass the limit temperature even when only employing passive means for decay heat removal. The limit fuel element temperature of 1600 °C had been proven without doubt by large-scale experiments. However, by employing this feature, the power density must be relatively low. This, in turn, necessitates many large RPVs and consequently large masses of graphite for neutron moderation. According to the results of an HTR-PM standard design, the specific weight – in terms of generated power – of an HTR-PM RPV is about 10 times that of a PWR. HTR-PM and PWR use, in essence, the same vessel material of low alloyed steel, while the HTR-PM vessels do not need resurfacing welding of stainless steel, which makes its specific costs decline somewhat. The quoted price of RPVs and reactor internals for an HTR-PM power plant is about 8 times that of a modern PWR in terms of equal power generation.

4.2.2. *Other NSSS equipments*

Steam generators: Compared to PWR steam generators, HTR-PM steam generators have smaller heat transfer coefficients on the primary helium side, while the temperature difference between its primary and secondary side is much larger. These two effects can compensate each other and should achieve a similar value of about 20 m^2 heat transfer surface per MW_e power generated.

Blowers or main pumps: Helium blowers belong to non-safety grade components while the main pumps of a PWR are safety grade. Helium blowers transmit high-pressure helium. The density of helium is low, which is an unfavorable factor. However, the temperature difference at the inlet and outlet of an HTR reactor is about 500 °C, while it is only 40 °C for a PWR. The disadvantage of the low helium density can be mostly compensated by the allowable large temperature difference. The specific motor power for HTR-PM helium blowers and for PWR main pumps should be similar: about 15–35 kW per MW_e generated power.

Control rod shut-down systems: An HTR-PM plant relies on continuous fuel charging/discharging to maintain core criticality. The shut-down system is used for power regulation and reactor shutdown. The temperature difference between shutdown condition and operating conditions is large, which – in combination with the very strong negative temperature coefficient of reactivity – means that more reactivity has to be compensated for. Thus, the advantages of (1) continuous fuel charging, (2) very high reactor exit temperatures and (3) a favorable negative temperature coefficient have to be paid for. Nevertheless, the number of control rod systems should be similar for an HTR-PM and for a PWR of equal power output.

The costs for primary pipelines and pressurizer in PWR can be mostly avoided for HTR-PM plants.

By summing up the above analyses, in principle it is found that for a well-designed HTR-PM, the capital cost of the other NSSS components has no great difference from PWR. The cost of these components depends more or less only on the plant power.

4.2.3. *Reactor auxiliary systems*

There are about 40–50 auxiliary systems for a second generation PWR, and 60–70 nuclear grade pumps and blowers. One knows from HTR-PM practice that these plants need less than 10 auxiliary systems, while, in addition, the pumps and blowers are non-nuclear grade. As far as the third generation evolutionary PWR is concerned, its redundancy degree is increased and the number of the above systems and components is increased further.

4.2.4. *I&C and electrical systems*

The needed capacity of an HTR-PM emergency power supply system is very small, and the allowed start-up time of the system is much longer (many hours versus less than 1 min). As the number of reactor auxiliary systems is decreased, I&C equipments also becomes significantly less.

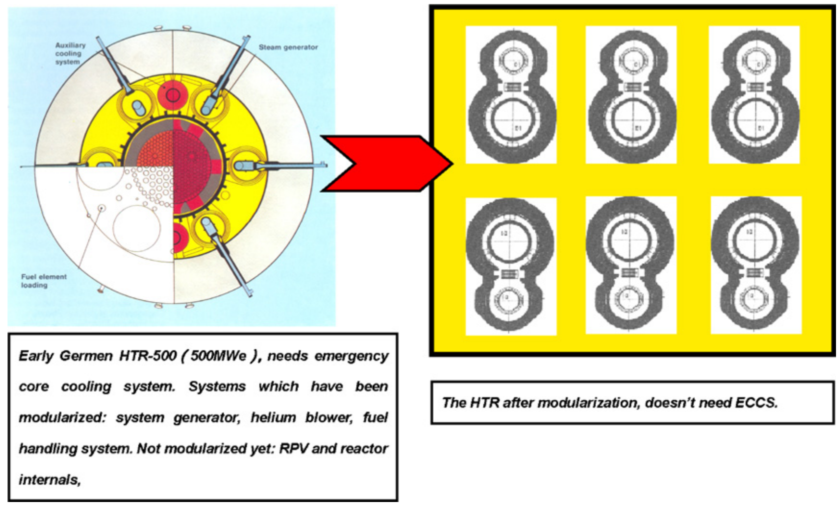

Fig. 8. Comparisons of a traditional HTGR and modern MHTGR designs.

Fig. 8 shows a comparison of a traditional pebble-bed HTGR and a modular HTGR. The graph on the left is the HTR-500 designed by ABB-HRB Company in the early 1980s. Its electric power is 500 MW with 6 steam generators and 6 blowers. The reactor has a pebble-bed core and the whole primary system is installed in one pre-stressed concrete pressure vessel. In this reactor, steam generators, blowers, fuel elements and control rods have already been modularized, while the reactor core and the pressure vessel are not. As the reactor core is rather large, it is impossible to limit – by passive means only – the highest attainable fuel elements temperature below 1600 °C. Without an active system of decay heat removal the maximum fuel element temperatures would reach more than 3000 °C even for a loss of coolant/depressurization accident. Clearly, the coated fuel particles would loose their capabilities of retaining all radioactive fission products. Therefore, this type of reactors needs an elaborate emergency core cooling system. The right chart depicts a 6 module MHTGR plant. In a simplified way one could imagine to just divide the reactor core in the left chart into 6 parts, which then forms 6 modules with each module consisting of one reactor core plus one steam generator and plus one helium blower, thus ensuring the inherent safety features and becoming a multiple module MHTGR plant. One clearly realizes that most equipments of an HTGR have already been modularized.

Hence, the major focus of designing an MHTGR is to modularize the RPV and the reactor internals. We can find the similar situation in PWRs, where the steam generators, the main coolant pumps, the fuel elements and the control rods have also been modularized, while the RPV and the core internals have not. There is no significant plant capital costs difference between a Westinghouse $3 \times 300\,\mathrm{MW_e}$ steam generator PWR and an ABB-CE $2 \times 500\,\mathrm{MW_e}$ steam generator PWR.

In conclusion, the key issue of HTR-PM economics is whether the increased costs of RPVs and reactor internals can be made up by factors like system simplification and modularization.

4.3. Capital cost estimates of HTR-PM reactor plant equipments

Fig. 9 shows capital cost estimates of PWR and HTR-PM reactor plant equipments.

The first column refers to the capital costs of a PWR plant. It has a capacity of $2 \times 1000\,\mathrm{MW_e}$ and is a mature *N*th-of-a-kind design. The total costs of all the PWR reactor plant equipments are normalized to 100. The second column refers to the capital costs of a first-of-its-kind HTR-PM demonstration plant with a capacity of $200\,\mathrm{MW_e}$ ($1 \times 458\,\mathrm{MW_{th}}$). The given values are based on the results of enquiries conducted for in the HTR-PM preliminary design. The cost data of this column are original given in Chinese currency and converted to the same unit of PWR costs which is given in the first column. The values given in the third column indicate the upper limit estimate, which is simply 10 times the value of the second column. The cost reduc-

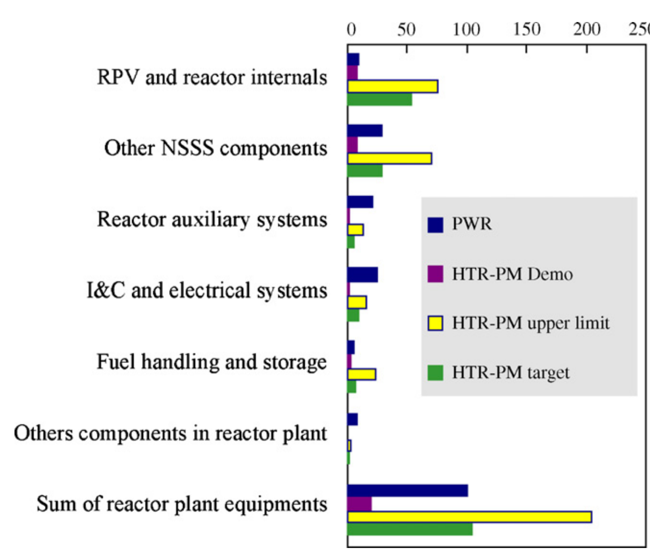

Fig. 9. Capital cost estimates of HTR-PM reactor plant equipments.

tions due to sharing the systems in a 10 NSSS module plant and the mass production are not taken into account. The fourth column shows the estimates of an HTR-PM target plant, which is a $2 \times 1000\,\mathrm{MW_e}$ *N*th-of-a-kind plant, i.e. sharing the systems in the plant and considering cost reductions due to experience and due to mass production. The costs shown in these columns are also of the same unit as the first column.

RPVs and reactor internals: An HTR-PM has much higher RPV and reactor internals costs. The target plant-estimate assumes a 30% cost reduction due to mass production.
Other NSSS components: An HTR-PM should have similar 'other NSSS component costs' as a PWR. The upper limit gives about twice the cost-estimates compared with PWRs. However, for the target plant these costs should approach to the same level as for PWRs.
Reactor auxiliary systems: Even a first-of-a-kind HTR-PM still has less reactor auxiliary system costs than a mature PWR. We expect this value to be reduced to an even smaller value when systems like, e.g., the helium purification system, etc., are shared for all the different NSSS modules, and when considering mass production and gained experience.
Fuel handling system and storage: An HTR-PM plant has still higher fuel handling and storage costs since there exists fewer experience for the on-lined refueling machine. However, it is expected that – with gaining experience – these costs will be reduced considerably for the *N*th-of-a-kind plant.
Other components in reactor plant: Not a significant issue.

In summary, an HTR-PM upper cost estimate for reactor plant equipments is found to be a factor two compared to the costs of reactor plant equipments for PWRs. This is mostly due to the higher costs of RPVs and reactor internals. However, it has to be noted again that here we compare a mature PWR with cost estimates obtained for a first-of-its-kind HTR-PM. As explained above, we estimate the target cost for a *N*th-of-a-kind HTR-PM plant to be at least quite similar to PWRs.

4.4. Capital cost estimates of HTR-PM plants

Fig. 10 gives capital cost estimates of HTR-PM plants. The meanings of the different columns are the same as in Fig. 9. The total plant cost of a PWR is also normalized to 100 and the other data are also, as explained above, converted to the real investment currency relationship.

Reactor plant equipments: As shown in Fig. 9, an HTR-PM upper limit for plant equipment costs is shown to be twice of those for the equipment costs for a PWR of the same power rating. The HTR-PM target plant is expected to exhibit similar costs. However, the costs for reactor plant equipments, e.g., for PWRs, accounts only to about 23% of the total plant capital cost.
Turbine plant equipments: An HTR-PM plant shows about a 25% reduction in turbine plant equipments compared to a PWR. An HTR-PM can use conventional turbine-generators with high pressure super-heated steam and achieves a much higher efficiency. According to the quotations obtained for the $200\,\mathrm{MW_e}$ HTR-PM demonstration plant, the specific costs of the HTR-PM turbine plant equipments are about 75% of those valid for a PWR plant. Further cost reduction is expected when a larger turbine-generator is needed for a larger multiple NSSS module plant. The estimation of 75% should be conservative.
BOP: No significant difference.
Buildings and structures, construction and commissioning: No significant difference, so far. It should be noted, however, that any cost reduction of the simple containment or confinement structure needed for an HTR-PM plant has not yet been taken into account.
First load fuel: No significant difference.
Engineering and design, project management, owner's cost: The modularization of an HTR-PM plant should show a reduction in these items. As an upper limit for an HTR-PM plant here we assume the same value as for PWRs; for the HTR-PM target plant we consider a reduction of 20%.
Financial cost, tax, insurances, contingencies: Less construction time and modularization should reduce the HTR-PM's costs. We assume an HTR-PM upper limit to have the same value as the value valid for a PWR, the target plant is expected to have a reduction of 20%.

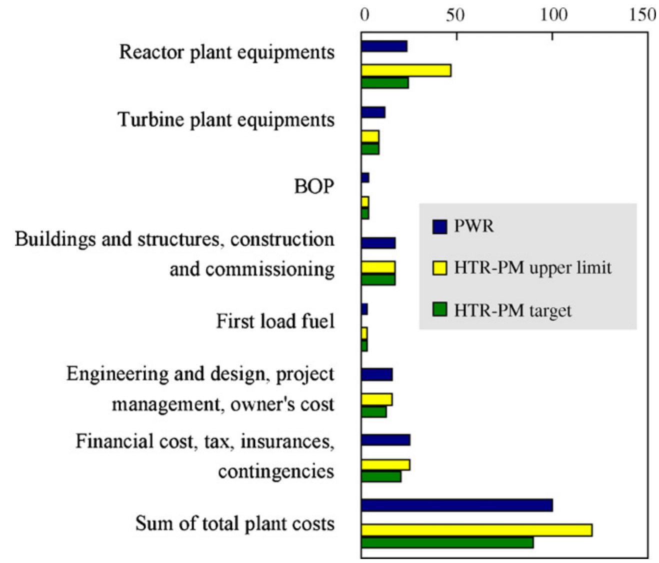

Fig. 10. Capital cost estimates of HTR-PM total plant.

Licensing approaches and roles in HTR-PM demonstration project are similar to those of PWRs, as we infer from our licensing experience of the HTR-10 project. If, however, the licensing and regulatory commissions will give credit to the inherent safety features by granting, e.g., lower equipment classification or even account for a very much reduced emergency preparedness of an HTR-PM, then the total plant costs are expected to decrease further.

Under the above assumptions, it is found that the maximum costs of an HTR-PM plant will not exceed the costs of an equivalent PWR by more than 20%. The fact that the RPV and reactor internals accounts only for ∼2% of the total plant costs greatly reduces the influence of the specific modular designs of an HTR-PM. Therefore, we even expect the costs of an HTR-PM target plant to be about 10% less than the costs for an equivalent PWR plant. In conclusion, our estimates show that the capital costs of an *N*th-of-a-kind HTR-PM plant with multiple NSSS modules should be in the range of 90–120% of the costs of a PWR. Further reductions are expected to be possible.

The above analysis is based on the data of HTR-PM practice until now. In order to verify the results, the cost data of another PWR plant are used for similar analysis and it is found that the difference between the results of the two analyses is smaller than 2%.

Fig. 11 tabulates shortly our reasoning why we believe that high RPV and reactor internals costs of an HTR-PM can be more than compensated.

HTR-PM RPVs and reactor internals costs are about 8 times of those costs for an equivalent PWR plant. However, the fact that PWR RPV and reactor internals costs contribute to only 2% of the total plant costs limits the cost increase effects of a multitude of RPVs. As indicated in the figure, HTR-PM reduction in reactor auxiliary systems, I&C and electrical systems compensate about 50% of the increase; HTR-PM reduction in turbine plant equipments, mass production of RPVs and reactor internals compensate additionally 40%; reduction in project management and engineering, schedule and financial cost would decrease the cost once again by 50%.

From the above analyses, the following four routes for attaining economical viability with MHTGRs are straight-forward:

- Combine multiple NSSS modules to one turbine-generator in one plant to achieve a large plant capacity.
- Reduce the costs of RPVs and reactor internals by mass production.
- Share the auxiliary systems as much as possible in one plant.
- Reduce the workload in engineering and project management and shorten construction schedule by making use of modularization and inherent safety characteristics.

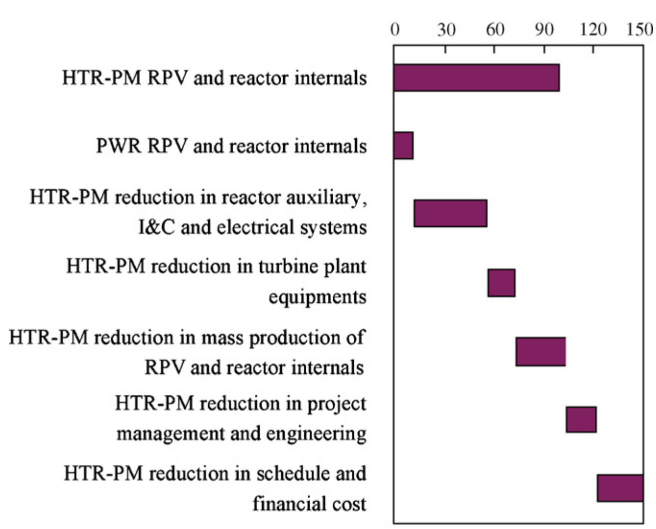

Fig. 11. Cost compensation of HTR-PM RPV and reactor internals.

The above statement is still a hypotheses – albeit a very convincing one – that has yet to be proved. To prove this firm expectation is the main aim of the Chinese HTR-PM project.

4.5. Comparison of two HTR-PM designs

Table 3 shows a comparison between two reactor designs for the HTR-PM project:

(1) a two zone reactor of 458 MW_{th} (1×458 MW_{th}), and
(2) two reactors of 250 MW_{th} each of one-zone design.

To our own surprise we found that cost reduction for the 1×458 MW concept is not as high as originally expected. The reasons are as follows:

(1) In order to reduce the flow resistance of helium, the primary pressure of the 458 MW reactor – having a larger diameter – amounts to 9.0 MPa, while the 250 MW reactor – having a smaller diameter – needs only 7.0 MPa. Therefore, the total weight of the two pressure boundary components of the 2×250 MW reactors is only 14% higher than the weight of the pressure boundary components of the 458 MW design.
(2) The 458 MW design requires 3 sets of fuel discharge systems.
(3) Considering the necessary replacement of the graphite central reflector of the 458 MW_{th} plant, this reactor building is higher and larger.

In the end, the equipment costs for the 2×250 MW_{th} reactor demonstration plant will increase by 15%, the total plant cost by 10%, while the power capacity is even increased by 5%. Overall, 5% more specific costs are estimated for the 2×250 MW HTR-PM demonstration plant.

According to the analysis in this paper, the cost difference of the future Nth-of-a-kind multiple NSSS Modules HTR-PM plant is also limited and will be less than 5%. Considering the technical uncertainties of the 458 MW_{th} two-zone design discussed in this paper, the 2×250 MW design seems to be more attractive.

Table 3
458 MW and 2×250 MW HTR-PM designs

	458 MW	2×250 MW
RPV weight	1	2×0.57
Graphite weight	1	2×0.60
Metallic reactor internals weight	1	2×0.86
Blower power	1	2×0.57
Control rods	24	2×10
Small absorption sphere systems	8	2×20
Fuel discharging systems	3	2
Volume of the reactor plant building	1	0.96
Reactor protection systems	1	2
Main control room	1	1
Helium purification systems	$2 \times 100\%$	$2 \times 100\%$
Fresh fuel and spent fuel systems	$1 \times 100\%$	$1 \times 100\%$
Emergency electrical systems	$2 \times 100\%$	$2 \times 100\%$

4.6. Power generation costs

The HTR-PM plant adopts the mode of continuous fuel loading and discharging. This could eventually lead to a 10% higher load factor. For a small pebble fuel production needed, HTR-PM fuel costs could be higher than fuelling costs for the current PWRs. However, if a further increase in fuel burn-up is achievable and a large-scale commercial fuel production is demanded, it is believed to be certain that the fuel costs of HTR-PM plants will reach the PWR level.

4.7. Power plants of small-scale

In the above analysis, it is assumed that HTR-PM plants and PWR plants have equal electrical power output. However, for plants of small-scales, specific costs would increase due to infrastructure building at site, workload of engineering and project management and other factors. Nevertheless, modularization of HTR-PM plants tends to bring benefits in terms of cost reduction when down scaling seems to be desirable. Smaller HTR-PM plants with a fewer number of modules would cost less than PWR plants of similar capacity.

5. Conclusions

This paper analyzes the capital costs for MHTGR plants and PWR plants based on the same plant capacities. The following are the main conclusions:

(1) The costs for the reactor pressure vessel and reactor internals of PWRs account for only 2% of the total plant costs, so that increases in these costs have limited influence.
(2) The main difference between the costs of an HTR-PM power plant and a PWR power plant is that the costs of RPVs and reactor internals increase significantly with an HTR-PM. About 50% of this increase could be compensated by simplification of the systems. The rest is expected to be compensated by the cost reduction of the turbine plant equipments, by benefits of modularization and by a shorter construction schedule as well as by less workload of design and engineering services.
(3) Our estimates show that the capital costs of an *N*th-of-a-kind HTR-PM plant with multiple NSSS modules should be in the range of 90–120% of the costs of a PWR. Further reductions are expected to be possible.
(4) The routes for attaining economical viability with MHTGRs are straight-forward: adopt multiple NSSS modules and one turbine-generator for one plant to achieve large capacity; reduce the costs of RPVs and reactor internals through mass production; share the auxiliary systems as much as possible in one plant; reduce the workload of design and engineering management; shorten construction schedule by making use of modularization and inherent safety characteristics.
(5) It is estimated that the specific costs of a ready-to-build $2 \times 250\,MW_{th}$ modular plant will be only 5% higher than the specific costs of one $458\,MW_{th}$ plant. When considering the technical uncertainties of the latter, a $2 \times 250\,MW_{th}$ modular plant seems to be more attractive.

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